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Paramati, Sudharshan Reddy; Alam, Md Samsul; Hammoudeh, Shawkat; Hafeez, Khalid

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Sudharshan Reddy Paramati
School of International Business; University of Dundee, UK
s.paramati@dundee.ac.uk

Md. Samsul Alam
Leicester Castle Business School, Faculty of Business and Law, De Montfort University, Leicester, UK.
samsul.alam@dmu.ac.uk

Shawkat Hammoudeh
Lebow College of Business,
Drexel University, Philadelphia, PA, USA
shawkat.hammoudeh@gmail.com

Khalid Hafeez
Leicester Castle Business School, Faculty of Business and Law, De Montfort University, Leicester, UK.
khalid.hafeez@dmu.ac.uk

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Long-run Relationship in between R&D Investment and Environmental Sustainability: Evidence from the European Union Member Countries

Abstract

The researchers, environmental scientists and policymakers around the world are exerting substantial efforts to mitigate the growth of CO_2 emissions to save the planet. A number of measures and initiatives, such as, energy efficiency, renewable energy technologies and emission-control are proposed in order to reduce CO_2 emissions. This study examines the long-run relationship between R&D investment and environmental sustainability in a panel of 25 European Union (EU) member countries over a period of seventeen years (1998 to 2014). We use robust and reliable econometric methods to capture the interactions between R&D investment on renewable energy consumption and CO_2 emissions. The findings confirm that the growth of R&D expenditures promotes renewable energy consumption and plays a significant role in reducing CO_2 emissions in the sample countries. Furthermore, the findings suggest that increasing the share of renewable energy consumption in the total energy mix also reduces CO_2 emissions. Given these results, we suggest that the EU policymakers provide more financial and regulatory assistance to the R&D activities, specifically in the energy sector, to ensure promoting low carbon economies in this region.

JEL Classification: F21, G15, O32, P28

Keywords: R&D, renewable energy, carbon emissions, sustainability

1. Introduction

The rapid environmental degradation as a result of using traditional energy sources such as fossil fuels is a global phenomenon[1]. The rise of CO_2 emissions from the consumption of fossil fuels has led scholars, policymakers and regulators to undertake various initiatives and actions, both at the national and international levels, to help reduce the greenhouse gas (GHGs) emission impact. One of the early global policy level efforts was led by the Kyoto treaty, the global environmental agreement that was signed by 37 industrialized countries and the European community, underpinning international commitment to fight the global warming by reducing greenhouse gas concentrations in the atmosphere. According to this treaty, the signatories are committed to reduce their country level GHGs emissions by at least 5% during the period 2008-2012, and by additional 18% in the years 2013-2020, taking 1990 as the baseline. The Paris Climate Conference (COP 21), that took place in December 2015, was a wider global initiative in this regard. In this conference, 195 committing countries adopted the first-ever universal and legally binding global climate deal to set up a long-term goal of curbing the increase in global average temperature well below 2°C (Zafar et al., 2019).

To minimise the greenhouse gas emissions emanating from the fossil fuels and to ensure sustainability of economic development, a wider use of the renewable energy is considered as the most important measure (Ummalla and Samal, 2018). Therefore, an increase of renewable energy in the total energy mix is crucial for creating a balanced and sustainable energy economy. The diversity of energy mix also accrues other benefits too. For example, energy from the renewable sources can enhance the security of energy supplies. It can also address local environmental pollutions, particularly in the EU economies which are

[1] Fossil fuels consumption, predominated by coal, oil and natural gas, had accounted for 81.3% (an equivalent of 11,360 Mtoe) of the global primary energy supply in 2017, emitting 99.3% of the global carbon (CO_2) emissions.

the focus of this study due to their strong commitment to combacting pollution. The growth of renewable energy sources may also have the potential to stimulate employment opportunities in these economies, through the creation of jobs in new ‘green’ technologies and in related ancillary activities. However, the overall share of the renewable energy in the total energy mix is remained very low. According to the World Bank (2020) report, the renewable energy makes up only 18% of the total global energy consumption in 2015[2]. Nevertheless, the renewable energy is a promising source of future cleaner energy. Its share needs to increase substantially and rapidly to meet the CO_2 emissions cap agreed in the Kyoto protocol and subsequently in the Paris agreement. Therefore, it is worth a fuller examination of its merits.

To underpin the long-term contribution of renewable energy to a sustainable energy system, R&D activities should be encouraged in order for nations to develop and adopt renewable energy technologies. Theoretically, R&D can increase efficiency, cut cost and improve productivity, which in turn contributes to greater economic growth. More specifically, R&D can improve the competitiveness of renewable energy technologies either by cutting their capital cost through reducing the energy and raw materials required, or by enhancing the efficiency of renewable energy production. Therefore, there is a particular need to ensure the adequacy of R&D investment in the energy sector to support a wider deployment of modern renewable energy technologies. However, according to International Energy Agency (IEA, 2015a) the global R&D investment in renewable energy remains low during the last four decades, amounting only to approximately USD 17 billion in 2014. The IEA believes that the funds currently allocated to renewable energy R&D are insufficient to develop viable renewable energy innovations to be able to meet the United Nations Strategic Development Goals (UNSDGs) of climate change. This is vindicated by the fact that the then

[2] For details, see https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS

IEA Executive Director Maria van der Hoeven emphasized the importance of R&D investment in renewable energy innovations in her speech at the launch of the "Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action" (IEA, 2015b. p1).[3]

One reason for the insufficient R&D investment in the renewable energy sector could be the lack of understanding by the policymakers of the potential benefits of energy R&D spending. This empirical study aims to provide better guidelines of the benefits of R&D investment in terms of improving environmental sustainability performance and its impact on reducing carbon emissions. For example, if the policymakers are made clear how each unit of R&D investment can result in the reduction of CO_2 emissions (per tonne), and then it gives them hard evidence to promote R&D investment in the renewable energy sector. However, according to our best knowledge, there is no such empirical study that underpins this issue when we embarked on this research. This study makes an effort to address this gap in the literature by resolving two objectives. Firstly, it aims to empirically examine the effect of R&D investment on both renewable energy consumption and CO_2 emissions in the EU economies[4]. Secondly, it investigates the impact of renewable energy consumption on CO_2 emissions.

By fulfilling these objectives, this study makes three significant contributions to the existing body of knowledge in the area of R&D investment and environmental sustainability. First, to our best knowledge, there is no published empirical research that examines the

[3] *"But we all know clean-energy deployment is not at the level where it needs to be. It is now crucial for governments and other stakeholders to take effective decisions for energy sustainability. This will not be possible by relying on yesterday's technology and policies. It is clean-energy innovation that will get us on the right path. With current policies, energy-related carbon emissions will exceed 50 gigatonnes of CO_2 in 2050. We are setting ourselves environmental and energy access targets that rely on better technologies. Today's annual government spending on energy research and development is estimated to be USD 17 billion. Tripling this level, as we recommend, requires governments and the private sector to work closely together and shift their focus to low-carbon while technologies".*

[4] UK was part of European Union (EU) when the data for this research was collected. UK has ceased to be part of EU since 31 January 2020.

relationship between R&D spending[5] and renewable energy consumption in the chosen 25 EU countries. Second, the analysis follows a widely used theoretical model to form the relationship among R&D, renewable energy and carbon emissions. More precisely, we use IPAT theoretical model proposed by Ehrlich and Holdren (1971) to identify the factors to minimize carbon missions. Thirdly, we employ multiple econometric methodologies that generate robust and reliable findings on the relationships between R&D spending, new energy sources and carbon emissions.

The EU is considered as an interesting case study since this region is the pioneer in the production and consumption of renewable energy and over the years has demonstrated a solid commitment to R&D investment in the renewable technology sector. Europe is by far the largest 'green' investor in the renewable energy R&D as well. According to the European Commission (2020), the EU's primary production of renewable energy from all sources was 1029 TeraWatt hours (TWh) in 2019, which is 37.5% of its total primary energy production. In 2018, the EU's renewable energy consumption accounted for 18.9% of its total energy consumption, which is expected to increase in future. For example, under the EU's energy and climate goals for 2030, the region has already committed to a new renewable energy target of at least 27% of final energy consumption by 2030. In the case of the R&D investment, the EU is the largest investor, leading China to a distant second. In 2014, the EU committed to invest US$4.3 billion in renewable R&D, nearly twice as much to China (of US$2.4 billion). Such R&D investments will have a significant impact on technological innovations by raising energy efficiency and promoting renewable energy production, which in turn should reduce CO_2 emissions.

Our study employs a balanced panel data during the period of 1998 to 2014 in the 25 EU member countries. In terms of the methodology, the paper investigates the long-run

[5] The data on energy R&D are not available, so we use total R&D expenditure in a country.

renewable energy and CO_2 emission elasticities using the FMOLS methodology after the validating the necessary preconditions including the order of integration, and cointegration approach. From a robust and reliable econometric analysis, the findings of this study show that R&D expenditures significantly improve renewable energy consumption and environmental protection in the long run in the 25 EU member countries under study. Further, the results also suggest that increasing the consumption of renewable energy sources ensures low CO_2 emissions. Given these findings, we offer important policy implications for the EU economies. More specifically, we suggest that the policymakers of the EU countries provide sufficient financial and regulatory support to R&D activities in the renewable energy sector (Garrone and Grili, 2010), which should bring significant innovations in the renewable energy production and carbon emission-controlling technologies. The innovations will eventually help those EU economies ensure low carbon economies and set the path towards sustainable economic development in the region.

The remainder of this paper as follows. Relevant literature is presented in Section 2 while some stylized facts regarding R&D, clean energy consumption and CO_2 emissions for sample countries are displayed in Section 3. Section 4 presents a statistical description of the data and the empirical methodology. Section 5 provides the empirical results. Section 6 summarises the paper with policy implications.

2. Literature review and hypothesis development

2.1. R&D, technological knowledge spillovers and renewable energy

R&D is considered the knowledge capital that enters the production function along with labour, physical capital and the rate of disembodied technical (Griliches, 1980; Hall and Mairesse, 1992). Similarly, other researchers including Romer (1990), Segerstrom et al. (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992) consider R&D as a determinant of total factor productivity (TFP) which is part of the production function. The R&D factor is considered a positive marginal product for the purpose this study, and an increase in the knowledge capital implies an increase in the output of renewable energy.

In addition, recent research views R&D, as a factor having an indirect effect on productivity as well that realises by the speed of technological diffusion and absorption. Therefore, the important channel through which R&D promote renewable energy is the technological knowledge development and spillovers (Miremadi et al., 2019). For example, Branstetter (2001) suggests that the diffusion of technological knowledge derived from R&D has a considerable impact on innovation and promotion of renewable energies from different sources. In this context, Keller (2004) illustrates that there are two types of transferable technological knowledge, namely tacit knowledge and explicit knowledge that are acquired from R&D. The tacit knowledge (e.g., personal wisdom and experience) is difficult to diffuse and communicate to others, while the explicit knowledge (e.g., scientific publications) can be easily documented and shared to the wider users (Hafeez et al., 2018, 2019, 2020). Garrone et al. (2014) argue that energy R&D helps to create renewable energy knowledge which can be diffused across regions through various patents, licensing and scientific publications as well as conferences. Finally, Poirier et al. (2015) point out that the level of the cumulative knowledge and resources for renewable energy in a country largely depends on the international knowledge spillovers. Knowledge also forms the social capital to help technology firms to innovate and internationalise (Arroteia and Hafeez, 2020). The tacit and explicit knowledge can be shared by entrepreneurs using social network platforms (Hafeez et al., 2018). In fact, the management of knowledge has become an essential ingredient of management competence in this day and age to leverage innovation and deliver the essential business functions (Brown et al., 2019). Co-locating similar companies in an innovation cluster enable to benefit from knowledge spillovers effect (Hafeez et al., 2016).

There are a number of studies that include technological innovations in their econometric models to examine the impact of R&D on energy consumption. Tang and Tan (2013), for instance, have investigated the relationship in between technological innovations and electricity consumption in Malaysia. By employing patent data as a proxy for technical innovations, the study reveals that the technological innovations help reduce electricity consumption significantly during 1970 — 2009. Therefore, the study underscores the importance of technological innovations toward decreasing fossil fuel consumption whilst ensuring the economic growth as well as environmental quality. Similarly, Fei et al. (2014) examined the impact of technological innovations on renewable energy and CO_2 emissions in the context of New Zealand and Norway during the period 1971-2010. B**y** applying the autoregressive distributed lag (ARDL) approach, these authors also use the number of patents as a proxy for technological innovations and find a long-run equilibrium relationship among the variables for both countries. Their findings also reveal that technological innovations make a significant contribution by increasing renewable energy consumption on one hand, and minimising CO_2 emissions on the other hand, in both countries.

However, Fei and Rasiah (2014) extended their earlier work to study four countries, namely Canada, Ecuador, Norway and South Africa. The authors introduced two new variables, namely, technological innovations and energy prices in the traditional electricity-growth nexus. Their findings indicate that technological innovations have the least impact on reducing the fossil fuel electricity consumption in the sample countries. Ahmed et al. (2016) inspected the causal association among technology innovations, biomass consumption and CO_2 emissions in the long-run using a panel data set of 24 European countries during the period 1980—2010. Considering number of patents as a proxy for innovation, their findings indicate that the technological innovations play a crucial role in facilitating the consumption of biomass energy that causes a reduction in CO_2 emissions. One of the major limitations of this study is that it only concentrates on biomass energy consumption, and we concur this limitation in our current study by focusing on renewable energy consumption from all major sources.

In summary, the literature suggests a positive correlation between the technological innovations and renewable energy consumption. Therefore, we propose the following null hypothesis to be tested subsequently in the empirical analysis section:

H1: R&D investments do not promote renewable energy consumption in the EU countries.

2.2. Dynamics of R&D and CO_2 emissions

Theoretically, the literature illustrates different models to describe the relationship between R&D and carbon emission, which also varies with the forms of the induced invocations. Baker et al. (2005) consider the impact of R&D on the global abatement cost function associated with a particular production function. The R&D planning problem is viewed first within a theoretical approach, and is subsequently followed by a stylized application using the Dynamic Integrated Climate-Economy (DICE) model. The impact of R&D on the uncertainty of climate change is, however, ambiguous in this model. Nordhaus (2002) uses a production function for generating new knowledge (i.e., production-possibility frontier) which is embedded into a model related to economics of global warming. The model determines the impact of innovation on greenhouse gas emissions and climate change. Their results show that the induced innovation reduce CO_2 emissions at a modest level in the short run, however, makes much substantial impact in the long run.

There are a few empirical studies that investigate the relationship amongst R&D and carbon emissions. Yang et al. (2014) employed panel data of 30 Chinese provinces during the period 1999- 2011 to analyse the effect of R&D on the industrial CO_2 intensity. The authors find that the local R&D activity and interregional R&D spillover helps decrease industrial CO_2 intensity significantly. In the same vein, Churchill et al. (2019) investigated the relationship in between R&D and carbon emissions in the G-7 group of countries. By using historical data from 1870—2014, their findings suggest that the association in between R&D and carbon emissions is time varying. However, the association is found to be negative for over three quarters of the sample period. Unlike previous studies, Alam et al. (2019) use firm-level data to explore the relationship between corporate R&D and carbon emissions. Employing robust econometric techniques from the data ranging from 2004 to 2016 for G-6 countries, the study shows that the R&D activities reduce carbon intensity significantly. More recently, Huang et al. (2020) examined how R&D activities can help to reduce carbon intensity in China. From a unique panel dataset during the period 2000 — 2016, the findings reveal that the R&D investment reduces carbon emissions right from the experimental and developmental phases of technological layout.

On the other hand, other studies claim that if the R&D technological innovations reduce energy consumption only marginally, this may not lead to any sizable reduction in the share of energy with regard to CO_2 emissions. For instance, Sagar and Zwaan (2006) fail to find any correlations among the public R&D spending, energy consumption per unit of GDP and the amount of carbon emissions per unit of energy consumption. Employing panel data from 19 OECD economies over the period 2003—2015, Koçak and Ulucak (2019) empirically investigate the role of public R&D in affecting carbon emissions. The findings of their study indicate that renewable energy R&D has no significant impact in reducing carbon emissions. Similarly, Petrović and Lobanov (2020) concur that where higher level of R&D (technology innovation) reduce the level of carbon emissions significantly in the long-run, the relationship between them is negative and neutral in the short run.

Given this theoretical and empirical background, we propose the following null hypothesis to examine the relationship between R&D and CO_2 emissions:

H2: R&D investments do not reduce CO_2 emissions in the EU countries.

2.3. Renewable energy consumption and CO_2 emissions

Through a careful analysis we can categories the existing literature on the relationship between renewable energy consumption and CO_2 emissions into three distinct groups. Firstly, as expected, a group of literature highlights a significant negative relationship between the two. Silva et al. (2011) is one of the earlier studies which explore the causal relationship between renewable energy used for electricity generation and CO_2 emissions. Their study uses a sample of four countries, namely Denmark, Portugal, Spain, and the U.S. during 1960—2004 period. Their findings reveal that the increasing portion of electricity consumption from renewable energy sources has a positive and significant impact on the reduction of CO_2 emissions for three sample countries, except the U.S. Shafiei and Salim (2014), employing the STIRPAT as the underpinning theoretical model, examined if such relationship exists for the OECD countries. Using a panel data for the period 1980 — 2011, their study concludes that the use of renewable energy reduces CO_2 emissions significantly in these sample countries. Therefore, they recommend that the OECD countries should promote renewable energy consumption to meet the challenge of climate change. Finally, Dogan and Seker (2016) investigated the impact of renewable and non-renewable energy on CO_2 emissions in the EU countries considering during 1980 — 2012 sample period. From various panel data estimations, authors show that renewable energy mitigates CO_2 emissions significantly.

Secondly, there is a group studies that reveal bidirectional relationship between renewable energy and carbon emissions. Considering six major emerging countries as a sample (Brazil, China, India, Indonesia, Philippines and Turkey), Salim and Rafiq (2012) attempted to identify the determinants of renewable energy consumption. Results from long-run econometric models indicated that there is bidirectional causality between renewable energy consumption and pollutant emissions in the short run. Applying the multivariate vector error-correction model (VECM), Rafiq et al. (2014) further examined the long run relationship between carbon emissions and renewable energy generation in the case of China and India. Their study uses time-series data for the period 1972—2011 and finds a bidirectional causal relationship between the variables in both countries. Apergis and Payne (2015) estimated the dynamic relationship among renewable energy generation, output and CO_2 emissions for a panel of 11 countries in South American during 1980 — 2010 period. The results of their panel error-correction model indicate that there is a feedback relationship in between renewable energy consumption and CO_2 emissions.

Thirdly, there is a stream of literature that reports no or little relationship in between renewable energy consumption and carbon emissions. Apergis et al. (2010), using panel data for 19 advanced and emerging nations during the period 1984–2007, investigated whether any relationship exists between renewable energy consumption and CO_2 emissions. Their results indicate that the renewable energy consumption has no substantial role in reducing emissions in these panel countries. Considering the U.S. as a case study, Menyah and Wolde-Rufael (2010) explored the causality in between the consumption of renewable and nuclear energy and carbon emissions during the period 1960–2007. The Granger causality test suggests no causal relationship. They argue that the cause of this insignificant relationship could be because the renewable energy consumption may not have reached a level where it can mitigate CO_2 emissions significantly. Finally, Ben Jebli et al. (2016) provide mixed evidence on the relationship between renewable energy consumption and carbon emissions in Sub-Saharan Africa.

Given the prevailing empirical and theoretical literature, we propose the third null hypothesis to be tested in this study:

H3. Renewable energy consumption does not reduce CO_2 emissions in the EU countries.

To sum up the existing literature, a few studies examine the impact of technology on energy consumption in single or multiple countries context. However, none of the existing literature investigates the impact of R&D on renewable energy consumption and carbon emissions, particularly focusing on EU countries. Our study is significantly distinctive from existing studies in terms of purpose, theoretical framework, data and sample period and methodology, and findings. Therefore, our study contributes to the sustainability literature by providing the first empirical evidence on the long-run relationship between R&D and environmental sustainability.

3. Some stylized facts on the sample countries

Table 1 presents the primary production of renewable energy in the EU countries in 2014. As indicated, this primary production of renewable energy was 196 Mtoe in 2014. Among the sources of renewable energies, the most important ones are solid biofuels and renewable waste followed by the hydropower, wind energy, solar energy and geothermal energy. There is a significant difference in the renewable energy mix across the EU nations due to their natural endowments and climatic conditions. For example, biomass and waste renewable accounted for more than 80% of renewable energy produced in the Czech Republic, Estonia, Finland, Hungary, Latvia, Lithuania, the Netherlands and Poland in 2014. However, the share of biomass and waste is also more than 50% of the total renewable energy production in all EU countries, except Ireland, Greece, Spain, Italy and Cyprus. Since Sweden, Austria and Slovenia are comparatively mountainous nations, more than one third of the total renewable energy of these countries comes from hydropower. Ireland, the Czech Republic, the UK and Greece are in the top position for wind energy production. Almost two thirds of the total renewable energy produced in Cyprus is from solar energy. Italy is in the top position of geothermal energy production where 22% of its renewable energy comes from geothermal, while Hungary is the distant second with a share of 6%.

[Insert Table 1 here]

Table 2 presents the renewable energy consumption in the EU countries in 2014. The highest share of renewables in gross final energy consumption was recorded for Latvia, while Sweden, Austria and Finland each reported that around one third of their final energy consumption was derived from renewables. The importance of renewables in gross inland consumption was relatively high for Denmark, Portugal, Romania and Slovenia. The share of various renewable energy consumptions suggests that biomass and renewables waste rank in the top place followed by hydropower, wind, solar and geothermal.

[Insert Table 2 here]

Table 3 presents country-specific summary statistics, using data from 1998 to 2014. The results show that among the EU members, Germany, France and Sweden have the highest level of renewable energy consumption, while Cyprus, Ireland, and Estonia have the lowest. Similarly, the highest CO_2 emitting EU members are Germany, the UK, Italy and France, while the lowest emitters are Cyprus, Latvia and Lithuania. Countries like Cyprus, the Netherlands, Belgium, and Ireland receive the highest FDI inflows (as a percentage of GDP) as against Greece which receives less than a 1% of their GDP. The average per capita GDP is higher than US$40,000 in the countries like Denmark, Sweden, the Netherlands, Ireland, Austria, Finland, Belgium and Germany. On the other hand, only Bulgaria and Romania have per capita GDP lower than US$10,000 per annum.

There are only four countries in the EU that have population of more than 50 million people including Germany, France, the UK and Italy, while Cyprus and Estonia have less than 2 million people. Table 3 also shows that countries like Sweden, Finland, Denmark, Germany, Austria and France have invested more money into R&D activities, whereas Cyprus and Romania have spent the least. Finally, the development of financial markets also significantly varies among the EU member countries. Overall, it implies that there is a considerable variation among the countries in terms of renewable energy uses, CO_2 emissions and R&D investments.

[Insert Table 3 here]

Figure 1 reports the key indicators of the study. It shows that the 25 EU member countries account for 8.89 percent of global CO_2 emissions in 2014, compared to 16.34 percent in 1998. Over this time period, the contribution to the global CO_2 emissions from the EU countries has thus significantly declined. On average, the EU member countries contributed 13 percent of the global CO_2 emissions. Similarly, the renewable energy consumption and R&D expenditure across these countries have gradually increased over the study period. Overall, these key indicators suggest that there is a considerable decline in the CO_2 emissions from the EU countries, while both renewable energy consumption and R&D investments have significantly increased over the period. Therefore, this suggests that the growth of R&D investment and renewable energy consumption might be helping the EU economies to mitigate CO_2 emissions.

[Insert Figure 1 here]

4. Data and empirical methodology

4.1 Nature of data and measurement

The current study makes use of the annual data for the 25 EU member countries over the period 1998 - 2014[6] which is the common data denominator among the 25 countries when we embarked on this study. That is, the selection of the sample period and the EU countries are based on the availability of data. We use a balanced panel data set for these selected EU countries in the analysis. The considered 25 EU member countries are: Austria, Belgium,

[6] At the time of analysis, the CO_2 emission data was available only until 2014 in the World Bank.

Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the UK as illustrated in Table 1. The measurement of the variables is provided below.

Renewable energy consumption (REC): This indicator includes energy consumption from all renewable resources: hydro, solid biofuels, wind, solar, liquid biofuels, biogas, geothermal, marine and waste. It is measured in Tera joule (TJ), a derived unit of energy in the International System of Units.

Carbon Dioxide Emissions (CDE): The CO_2 emissions are sourced from the consumption of fossil energy which includes emissions due to the consumption of petroleum, natural gas and coal as well as from natural gas flaring. These all are measured in kilotonnes (kt).

Foreign direct investment (FDI): The FDI is the net inflows of investment and is the sum of equity capital, reinvestment of earnings, other long-term capital, and short-term capital as shown in the balance of payments. This series shows net inflows (new investment inflows less disinvestment) in the reporting economy from foreign investors, and is divided by GDP.

GDP per capita (PI): Per capita income is the gross domestic product divided by midyear population. GDP is the sum of gross values added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is measured in constant 2010 U.S. dollars.

Total population (POP): Population is based on the de facto definition of population, which counts all residents regardless of their legal status or citizenship. The values shown are midyear estimates.

Research and development (R&D): The research and development expenditures are the current and capital expenditures (both public and private) on creative work undertaken systematically to increase knowledge, including knowledge of humanity, culture, and society, and the use of knowledge for new applications. R&D covers basic research, applied research, and experimental development. It is measured as a percentage of GDP.

Financial market index (FM): This index is an aggregate of financial markets' access, depth and efficiency indices.

The required data on CDE, FDI, PI, POP and R&D are obtained from the *World Development Indicators* (WDI) online database supplied by the World Bank, while the data on REC and FM are sourced from the 'Sustainable Energy for All' (World Bank) and the 'International Monetary Fund (IMF) online data bases, respectively. Before commencing on the empirical analysis, we converted all data series into natural logarithms, with the exception of FDI series, due to negative values. Previous researchers such as Alam et al. (2016), Bhattacharya et al. (2016), Paramati, Alam et al. (2016) and Paramati, Ummalla et al. (2016) document that converting the data series into natural logarithms helps to avoid the problems associated with distributional properties of the data series and suggest that the estimated coefficients can be interpreted as elasticities.

4.2 Estimation procedure

The present study aims to investigate the effect of R&D on renewable energy consumption and CO_2 emissions in the EU member countries. Further, it examines to what extent renewable energy consumption reduces CO_2 emissions in those countries. To achieve the first objective, i.e. the effect of R&D expenditure on renewable energy, we use the following empirical model:

$$REC_{it} = f\,(CDE_{it}, PI_{it}, R\&D_{it}, FDI_{it}, FM_{it}, v_i) \qquad (1)$$

Where; *REC*, *CDE*, *PI*, *R&D*, *FDI*, and *FM* denote renewable energy consumption, CO_2 emissions, per capita income, research and development expenditure, foreign direct investment, and financial markets, respectively. Similarly, countries and time periods are indicated by the subscripts i $(i = 1, ..., N)$ and t $(t = 1, ..., T)$, respectively, while v_i represents individual country fixed effects. The main purpose of Equation (1) is to empirically examine the effect of R&D on renewable energy consumption while accounting for other potential determinants in the model such as CO_2 emissions, per capita income, FDI, and FM.

Similarly, to investigate the impact of R&D expenditure and renewable energy on CO_2 emissions, we make use of the environmental theoretical model IPAT (Ehrlich and Holdren, 1971) to determine the drivers of CO_2 emissions. This theoretical model is built based on the association among the population, income, technology and the environmental impact. To account various other potential drivers of emissions, we base our empirical model on *STIRPAT* (Stochastic Impacts by Regression on Population, Affluence and Technology) approach (Dietz and Rosa (1994, 1997) as described below:

$$CDE_{it} = f\,(POP_{it}, PI_{it}, R\&D_{it}, FDI_{it}, FM_{it}, v_i) \qquad (2)$$

$$CDE_{it} = f\,(POP_{it}, PI_{it}, REC_{it}, FDI_{it}, FM_{it}, v_i) \qquad (3)$$

Equation (2) aims to identify the role of R&D in reducing CO_2 emissions. Finally, Equation (3) attempts to identify to what extent renewable energy uses reduce CO_2 emissions in a panel of the 25 EU member countries. All these equations account for the important control variables, including population (POP), in the models.

We begin our investigation by applying three panel unit root tests. Specifically, the common unit root process is examined using the Levin et al. (2002) (LLC) test, while the individual unit root processes are investigated by employing the Im et al. (2003) (IPS) test. Finally, we use the cross-sectional augmented panel unit root (CIPS) test, which is proposed by Pesaran (2007) based on the assumption of cross-sectional dependence. These tests help us to identify the stationary properties of the data series. We then move on to investigate the long-run equilibrium relationship among the variables of Equations (1), (2) and (3). For this purpose, we use the methodology that is suggested by Padroni (1999, 2004).[7] This test is developed using the Engle and Granger (1987) two-step procedure. The Pedroni cointegration test provides seven statistics for the tests of the null hypothesis of no cointegration in heterogeneous panels (Alam and Paramati, 2015). In the final step, we explore the long-run renewable energy and CO_2 emission elasticities using the FMOLS methodology by taking into account of weighted approach (Pedroni, 2000; Kao and Chiang, 2000). This technique helps us to account for heterogeneity in the estimation. A number of previous studies (e.g. Alam and Paramati, 2016; Bhattacharya et al., 2016; Paramati et al., 2016a) also use this technique to estimate long-run parameters

5. Empirical results and discussion

5.1 Order of integration of the variables

As a first step of the empirical analysis, as indicated earlier, we explore the order of integration of the variables by using three different panel unit root tests. The results of these panel unit root tests are displayed in Table 4. The LLC and IPS panel unit root tests work

[7] Other cointegration tests can be used here but we think this test with its seven statistics is suitable for our study.

under the assumption of cross-sectional independence in the series, while the CIPS test works under the assumption of cross-sectional dependence. All these unit root tests have the null hypothesis of a unit root (non-stationary) against the alternative hypothesis of no unit root (stationary). The results show that the null hypothesis of a unit root cannot be rejected for all of the variables at the level data. However, when these tests are applied to the first difference of the series, the null hypothesis is strongly rejected for all the variables and the result is statistically significant at the 1% or 5% level. These findings imply that all the variables have the same order of integration, i.e. I (1). Since all of the panel unit root tests confirm the same order of integration among the variables, hence there may be a cointegration relationship among the variables of Equations (1), (2) and (3) in the long run. This is investigated in the next subsection.[8]

[Insert Table 4 here]

5.2 Findings of long-run equilibrium relationships

Since the variables of Equations (1), (2) and (3) have the similar order of integration, therefore we explore the long-run association among these models using the Pedroni (1999, 2004) panel cointegration framework. The appropriate lag length for the estimation of these models is selected based on the Akaike Information Criterion (AIC). The results are reported in Table 5. The findings of Model-1 show that out of the test's seven statistics, two statistics under the within-dimension and two statistics under the in-between-dimension statistics is statistically significant. This means that there is a considerable long-run relationship among the variables under consideration. Similarly, the results of Model-2 and Model-3 indicate that four statistics under both the within-dimension and between-dimension approaches are statistically significant. These results also confirm a significant long-run association among

[8] We have applied a panel unit root test that takes into account of structural breaks (Carrion-i-Silvestre et al., 2005). However, the evidence from this test confirms that there are no structural breaks in the selected panel data series.

the considered variables. Given these findings, we strongly reject the null hypothesis of no cointegration among those variables and accept the alternative hypothesis of a cointegration relationship. These results establish that the variables in Model-1, Model-2 and Model-3 reach an equilibrium point in the long-run, despite of their varying association over time.

[Insert Table 5 here]

5.3 Findings of long-run renewable energy consumption and emission elasticities

The above results of the cointegration test confirm the long-run relationship among the variables, however, do not imply whether R&D increases or decreases renewable energy consumption and CO_2 emissions in the EU economies. Therefore, to understand the effect of R&D on renewable energy use and CO_2 emissions and assess the impact of renewable energy on CO_2 emissions, we employ the FMOLS framework for the empirical analysis.

The findings of applying the FMOLS models to Equations (1), (2) and (3) are presented in Table 6. The results of Model-1, in which the renewable energy consumption is served as the dependent variable and *CDE*, *PI*, *R&D*, *FDI* and *FM* are treated as the independent variables, are discussed below.

i. *Model 1: A 1% increase in the R&D expenditure raises renewable energy consumption by about 0.412%.*

The above result indicates that R&D has a significant positive effect on the renewable energy consumption in the EU countries, as indicated by the 0.412 R&D elasticity of renewable energy consumption. Similarly, per capita income and financial markets also have considerably positive impact on the renewable energy consumption. This means that the growth of R&D investment, per capita income, and financial markets promote renewable energy consumption across economic activities of the EU countries. Given these findings, we strongly reject the H1 null hypothesis of Subsection 2.1 which states that R&D does *not* promote renewable energy consumption in the EU countries.

ii. Model 2: A 1% increase in R&D expenditure decreases CO_2 emissions by 0.140%

On the other hand, the results of Model-2 in which the CO_2 emissions variable is considered to be the dependent variable, while R&D and the other variables are treated as the independent variables show that significant growth of the R&D expenditures seems to work in favour of reducing CO_2 emissions in the EU countries. Similarly, the findings also confirm that the FDI inflows and financial markets also reduce CO_2 emissions. These findings suggest that considerable growth of R&D expenditures, and financial markets promote more renewable energy uses, as the findings from Model 1 confirm. As a result of these findings, it is hoped that growth in R&D, FDI and financial markets will help those economies minimize CO_2 emissions. Specifically, we argue that the financial markets reflect the increase in the listed shares of the service companies which consume less fossil fuel than the good-producing companies. The stock markets may also show support for companies with new technologies that reduce pollution, which may reflect the increase in awareness of the danger of climate change. This promises well for the future demand for the shares of companies that produce renewable energy. We also find similar impacts from per capita income and population on CO_2 emissions. Specifically, we argue that increasing income levels help individuals to adapt more environmentally friendly activities. Similarly, the population growth in this region of the world is not going to adversely affect the environment as people are becoming more aware of their environmental responsibilities. Based on these findings, we reject the null hypothesis H2 of Section 2.2 which argues that R&D expenditures do *not* decrease CO_2 emissions in the EU countries.

iii. *Model 3: A 1% increase in renewable energy consumption reduces CO_2 emissions by 0.236%.*

Finally, the findings of Model 3 where CO_2 emissions and renewable energy consumption are treated as the dependent and independent variables respectively imply that the growth of renewable energy consumption has a negative effect on growth of CO_2 emissions. Furthermore, the results show that the FDI inflows also have a considerable negative impact on the emissions. Based on these results, we argue that the renewable energy consumption reduces emissions by increasing the share of this consumption in total energy consumption, while the FDI inflows reduce emissions by increasing access to energy efficiency and emission-controlling technologies. As a result of these factors, both renewable energy consumption and FDI inflows are able to reduce the CO_2 emissions in the EU countries. Given these results, we reject null hypothesis H3 of Subsection 2.3 which hypothesizes that renewable energy consumption does *not* decrease CO_2 emissions in the EU countries.

[Insert Table 6 here]

For the robustness purpose, we again classified our sample countries into two groups based on their income levels. Specifically, the countries that have, on average during the study period, more than 15000 US$ are treated as high-income economies (Austria, Belgium, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal, Slovenia, Spain, Sweden, and UK); while the countries that have less than 15000 US$ are considered as low-income economies (Bulgaria, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia). This exercise will help us to understand whether the nature of the association among these key variables remain same or differs. The panel FMOLS results are displayed in Table 7. The results show that the growth in R&D

expenditure continues to promote renewable energy consumption across these two groups of economies. However, it is important to highlight that the impact of R&D is significantly higher in high-income economies than those of the low-income group. We also find that the effect of FDI inflows on renewable energy is positive in low-income economies, while its' impact is insignificant in high-income group. It makes sense that the FDI is more vital in low-income group as compared with high-income group. The evidences also reveal that the financial markets are having a negative impact in low-income economies, whereas their effect is positive in high-income group. This outcome also offers important practical knowledge. Specifically, it is widely known that the scope of the financial markets in these low-income economies is very limited; on the other hand, their role is much bigger in high-income economies. Therefore, the financial markets have a varying impact on renewable energy across these economies.

We also find that the R&D expenditure is not in a position to reduce CO_2 emissions in low-income economies; however, it does play a key role in mitigating emissions in high-income group. On the other hand, both FDI inflows and financial markets seem to help reduce emissions in low-income economies; whereas only financial markets work effectively in high-income economies to reduce it. It is important note that the renewable energy is playing a key role in reducing the growth of carbon emissions across these two groups. However, the impact is more in high-income economies than that of low-income countries. The FDI and financial markets continue to play a key role in reducing emissions in low-income group, despite R&D being replaced with renewable energy variable in the model. However, their impact changes, after introducing renewable energy into the model, on emissions in high-income economies. The overall take away knowledge from these estimates is that the R&D impact is still positive in driving renewable energy across these two groups of economies.

[Insert Table 7 here]

6. Conclusion and policy implication

During the last few decades, the world has seen tremendous detrimental changes in the climate due to the increasing greenhouse gas emissions around the world. Given the growing concerns of climate change and greenhouse gas emissions around the globe, this phenomenon has attracted the attention of international organizations, policymakers and environmental scientists who have recently been looking for ways to address them. Hence, all these authorities are making strenuous efforts to mitigate the CO_2 emissions by encouraging technological innovations in the energy sector and promoting the generation and use of renewable energy sources across economic activities. This has therefore motivated us to examine the effect of R&D investment on environmental sustainability, particularly focusing on renewable energy consumption and CO_2 emissions in a panel of 25 EU member countries. For this purpose, we have made use of annual data ranging from 1998 to 2014 and applied several robust panel econometric techniques. We believe the findings derived from this analysis will promote better understanding and be useful in enhancing renewable energy production and consumption and in pursuing CO_2 emission-controlling policies.

The empirical findings of this study confirm the presence of a significant long-run association among the variables: R&D, renewable energy consumption and CO_2 emissions. The results also show that the growth of the R&D expenditures positively contributes to more renewable energy production and consumption and helps reduce CO_2 emissions in the EU economies. The findings also assert that increasing the consumption of renewable energy mitigates CO_2 emissions. Given these findings, we strongly suggest that by increasing the R&D activities, the EU countries not only promote renewable energy technologies and production but also help mitigate CO_2 emissions by improving the access to emission-controlling technologies.

The major policy implications of this study are as follows. (i) since our findings on long-run elasticities indicate that the growth of R&D activities increases renewable energy consumption and reduces CO_2 emissions, thereby we argue that the policymakers of the EU countries should increase the funding allocated to the R&D activities so that they can bring more innovations to new and existing sources of energy, particularly renewable energy, and introduce more emission-controlling technologies such as catalytic converters to reduce CO_2 emissions at source (of the automobile exhausts). These new innovations in the energy sector will greatly assist EU countries to further promote the generation and use of renewable energy and combat the growth of CO_2 emissions. (ii) The results also show that the consumption of renewable energy also decreases CO_2 emissions.

Therefore, we suggest that policymakers initiate more effective policies and directives whether in terms of subsidies, tax credit and tax holidays, and others to attract more investments into the renewable energy sector, particularly from FDI inflows and portfolio investments in the stock markets. Such policies and directives should therefore encourage both domestic and foreign investors to investment more money into renewable energy projects. Consequently, there will be an abundant renewable energy generation which will not only meet the increasing demand for energy but also replace conventional energy sources. This will also ensure and prompt a low carbon economy and set path towards sustainable development in the EU member countries. Finally, we hope that this study contributes to the body of knowledge on the issue of the long run association between R&D investment, renewable energy consumption and CO_2 emissions in the EU countries since it is the first to address this nexus in the literature.

While this study adds significant contributions in academic knowledge and policy implications, it also offers some important directions for investors and technological companies. These results provide them hard evidence that any investment in the green technology area is worthwhile, subject to a long-term demand and would accrue long term benefits. However, the study has its limitations. First, we restricted our analysis in the context of EU member countries only. Future studies may consider investigating this relationship in other regions including East Asia, South Asia and Sub-Saharan Africa since the level of R&D expenditure; economic development and policies related to renewable energy are significantly different from one region to another. Second, due to data limitation, our analysis is conducted based on macro-level (country-level) data. Future researchers might examine the impact of R&D investment on renewable energy consumption by using micro (firm-level) data. We also recommend that the methodology adopted for this research is systemic and robust for underpinning such research and may be used by other researchers to explore other data set to measure the short- and long-term impact of these variables.

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Table 1: Primary production of renewable energy in the EU countries in 2014

Country	Total Renewable Production (Thousand toe)	Share (%) of total renewable production				
		Biomass & renewable waste	Geothermal	Hydropower	Solar	Wind
Austria	9370.00	55.80	0.30	37.60	2.70	3.50
Belgium	2857.00	75.80	0.10	0.80	9.40	13.90
Bulgaria	1842.00	63.60	1.80	21.50	6.90	6.20
Cyprus	111.00	17.80	1.40	0.00	66.70	14.10
Czech Republic	3656.00	89.00	0.00	4.50	5.40	1.10
Denmark	3144.00	61.50	0.10	0.00	2.60	35.80
Estonia	1186.00	95.40	0.00	0.20	0.00	4.40
Finland	10068.00	87.60	0.00	11.40	0.00	0.90
France	21002.00	63.10	1.00	25.70	2.90	7.10
Germany	36018.00	70.80	0.50	4.70	10.30	13.70
Greece	2329.00	47.10	0.50	16.50	22.20	13.60
Hungary	2051.00	89.20	6.30	1.30	0.50	2.80
Ireland	854.00	39.60	0.00	7.10	1.40	51.80
Italy	23644.00	42.20	22.10	21.30	8.90	5.50
Latvia	2371.00	92.30	0.00	7.20	0.00	0.50
Lithuania	1358.00	92.80	0.10	2.50	0.50	4.00
Netherlands	4555.00	86.00	0.80	0.20	2.10	10.90
Poland	8054.00	89.00	0.30	2.30	0.20	8.20
Portugal	5848.00	53.80	3.20	22.90	2.20	17.80
Romania	6090.00	61.90	0.50	26.60	2.30	8.80
Slovakia	1441.00	70.40	0.50	25.10	4.00	0.00
Slovenia	1180.00	50.10	2.70	44.40	2.80	0.00
Spain	18003.00	39.10	0.10	18.70	17.30	24.80
Sweden	16660.00	61.20	0.00	32.90	0.10	5.80
UK	9696.00	62.30	0.00	5.20	4.10	28.40
EU-28	195814.00	63.10	3.20	16.50	6.10	11.10

Table 2: Renewable energy consumption in the EU countries in 2014

Country	Renewable energy (%) of total energy consumption	Biomass & wastes	Geothermal	Hydropower	Solar	Wind
Austria	30.00	17.30	0.10	10.80	0.80	1.00
Belgium	6.30	5.00	0.00	0.00	0.50	0.70
Bulgaria	10.10	6.30	0.20	2.20	0.70	0.60
Cyprus	6.00	1.90	0.10	0.00	3.30	0.70
Czech Republic	8.80	7.80	0.00	0.40	0.50	0.10
Denmark	26.20	19.10	0.00	0.00	0.50	6.70
Estonia	12.80	12.00	0.00	0.00	0.00	0.80
Finland	29.40	25.70	0.00	3.30	0.00	0.30
France	8.60	5.50	0.10	2.20	0.20	0.60
Germany	11.30	8.00	0.10	0.50	1.20	1.60
Greece	10.00	5.00	0.00	1.60	2.10	1.30
Hungary	8.40	7.40	0.60	0.10	0.00	0.20
Ireland	7.10	3.30	0.00	0.40	0.10	3.30
Italy	17.60	8.50	3.50	3.30	1.40	0.90
Latvia	36.20	32.10	0.00	3.90	0.00	0.30
Lithuania	19.10	17.60	0.00	0.50	0.10	0.80
Netherlands	4.40	3.60	0.00	0.00	0.10	0.60
Poland	9.10	8.20	0.00	0.20	0.00	0.70
Portugal	25.00	12.80	0.90	6.10	0.60	4.70
Romania	19.00	11.80	0.10	5.00	0.40	1.70
Slovakia	8.80	6.10	0.00	2.20	0.40	0.00
Slovenia	18.30	9.50	0.50	7.80	0.50	0.00
Spain	15.20	5.80	0.00	2.90	2.70	3.80
Sweden	35.80	22.40	0.00	11.40	0.00	2.00
UK	6.40	4.50	0.00	0.30	0.20	1.50
EU-28	12.50	8.00	0.40	2.00	0.70	1.40

Table 3: Country-specific summary statistics, 1998-2014

Country	REC	CDE	FDI	PI	POP	R&D	FM
Austria	287527.64	66425.33	3.95	45028.83	8.24	2.38	57.54
Belgium	54664.87	106661.17	18.12	42257.79	10.63	1.98	44.92
Bulgaria	40918.06	46144.88	9.48	5734.60	7.66	0.52	10.77
Cyprus	3143.71	7229.60	73.49	28997.72	1.04	0.36	44.71
Czech Republic	90436.31	114422.26	5.68	17893.40	10.34	1.32	23.99
Denmark	102044.10	48066.17	2.88	57682.07	5.46	2.58	48.93
Estonia	24403.58	16978.86	9.49	13980.39	1.35	1.17	16.11
Finland	333060.46	57461.67	4.09	44350.59	5.28	3.34	63.42
France	623775.26	360564.03	2.25	39888.00	63.41	2.14	62.93
Germany	650670.31	790367.49	2.57	40350.28	81.85	2.55	74.44
Greece	70893.19	88766.21	0.63	25593.44	10.96	0.61	53.68
Hungary	58462.95	53236.43	10.87	12470.90	10.07	1.01	49.77
Ireland	17922.20	40510.64	16.42	48344.02	4.24	1.31	58.26
Italy	469577.94	427690.19	1.11	36211.45	58.32	1.13	72.92
Latvia	57106.58	7371.96	3.96	10566.16	2.21	0.52	8.86
Lithuania	36815.72	13616.00	3.68	10692.57	3.26	0.76	7.99
Netherlands	64757.88	176846.90	23.82	48899.03	16.35	1.79	74.80
Poland	206540.86	306626.99	3.56	10780.34	38.20	0.67	33.31
Portugal	162678.28	56834.40	4.15	21786.38	10.45	1.05	49.78
Romania	178801.84	90531.11	3.95	7096.71	21.12	0.44	6.63
Slovak Republic	30953.56	36867.59	4.34	14108.98	5.39	0.61	4.99
Slovenia	32146.56	15284.06	1.81	21670.39	2.02	1.73	35.07
Spain	370495.04	298100.78	3.24	29825.57	43.96	1.12	82.25
Sweden	559920.26	50102.44	5.42	49502.39	9.16	3.43	73.11
United Kingdom	136732.79	508878.22	4.76	38738.03	61.14	1.62	80.02

Notes: REC stands for renewable energy consumption (tera joule); CDE for total CO_2 emissions (kt); FDI for foreign direct investment, net inflows (% of GDP); PI for GDP per capita (constant 2010 US$); POP for total population (millions); R&D for research and development expenditure (% of GDP); and FM for financial market index. This is the complete sample that was available when we embarked on this research.

Table 4: Panel unit root tests

	Levin, Lin & Chu (LLC) test				Im, Pesaran and Shin (IPS) W-stat				Pesaran CIPS test			
Variable	Statistic	Prob.	Statistic	Prob.	Statistic	Prob.	Statistic	Prob.	Zt-bar	Prob.	Zt-bar	Prob.
	Null: Unit root (assumes common unit root process)				Null: Unit root (assumes individual unit root process)				Null: Unit root (assumes unit root process under cross-sectional dependence)			
	Level		First difference		Level		First difference		Level		First difference	
REC	-0.684	0.247	-6.537***	0.000	-0.453	0.325	-4.405***	0.000	-0.644	0.260	-8.455***	0.000
CDE	-0.097	0.461	-12.308***	0.000	3.159	0.999	-9.577***	0.000	2.833	0.998	-10.420***	0.000
FDI	0.160	0.563	-9.122***	0.000	-0.785	0.216	-8.924***	0.000	3.036	0.999	-11.590***	0.000
PI	0.820	0.794	-8.194***	0.000	3.343	1.000	-3.998***	0.000	2.579	0.995	-1.990**	0.023
POP	5.556	1.000	-10.334***	0.000	1.326	0.908	-6.552***	0.000	4.385	1.000	-2.211**	0.014
R&D	0.676	0.751	-2.800***	0.003	1.449	0.926	-2.807***	0.003	-1.166	0.122	-6.761***	0.000
FM	0.047	0.519	-10.019***	0.000	-0.155	0.439	-6.712***	0.000	1.441	0.925	-9.454***	0.000

Note: All the unit root tests are estimated using a constant and trend in the models. The asterisks ** and *** indicate the rejection of the null hypothesis of a unit root at the 5% and 1% significance levels, respectively.

Table 5: Panel cointegration test results

REC = f (CDE, PI, R&D, FDI, FM)					*CDE = f (POP, PI, R&D, FDI, FM)*				*CDE = f (POP, PI, REC, FDI, FM)*			
Alternative hypothesis: common AR coefs. (within-dimension)												
	Statistic	Prob.	Weighted statistic	Prob.	Statistic	Prob.	Weighted statistic	Prob.	Statistic	Prob.	Weighted statistic	Prob.
Panel v-Statistic	-0.895	0.815	-1.983	0.976	-2.741	0.997	-3.144	0.999	-2.428	0.992	-3.041	0.999
Panel rho-Statistic	2.878	0.998	3.106	0.999	3.466	1.000	2.996	0.999	2.836	0.998	2.459	0.993
Panel PP-Statistic	-3.453***	0.000	-4.631***	0.000	-6.752***	0.000	-10.457***	0.000	-5.733***	0.000	-9.216***	0.000
Panel ADF-Statistic	-4.601***	0.000	-5.015***	0.000	-6.441***	0.000	-7.539***	0.000	-5.674***	0.000	-5.514***	0.000
Alternative hypothesis: individual AR coefs. (between-dimension)												
	Statistic	Prob.			Statistic	Prob.			Statistic	Prob.		
Group rho-Statistic	5.055	1.000			4.719	1.000			4.174	1.000		
Group PP-Statistic	-5.534***	0.000			-13.657***	0.000			-13.617***	0.000		
Group ADF-Statistic	-4.708***	0.000			-8.041***	0.000			-5.145***	0.000		

Note: *** indicates the rejection of the null hypothesis of no cointegration at the 1% significance level.

Table 6: Long-run renewable energy and emission elasticities

Variable	Coefficient	t-Statistic	Prob.
REC = f (CDE, PI, R&D, FDI, FM)			
CDE	-1.594***	-48.186	0.000
PI	0.898***	48.260	0.000
R&D	0.412***	21.551	0.000
FDI	0.041	1.219	0.224
FM	0.043*	1.952	0.052
CDE = f (POP, PI, R&D, FDI, FM)			
POP	-0.390***	-73.759	0.000
PI	-0.008	-1.050	0.295
R&D	-0.140***	-10.783	0.000
FDI	-0.054***	-4.822	0.000
FM	-0.076***	-6.692	0.000
CDE = f (POP, PI, REC, FDI, FM)			
POP	0.531***	111.196	0.000
PI	0.197***	28.418	0.000
REC	-0.236***	-25.058	0.000
FDI	-0.118***	-11.443	0.000
FM	-0.014	-1.101	0.272

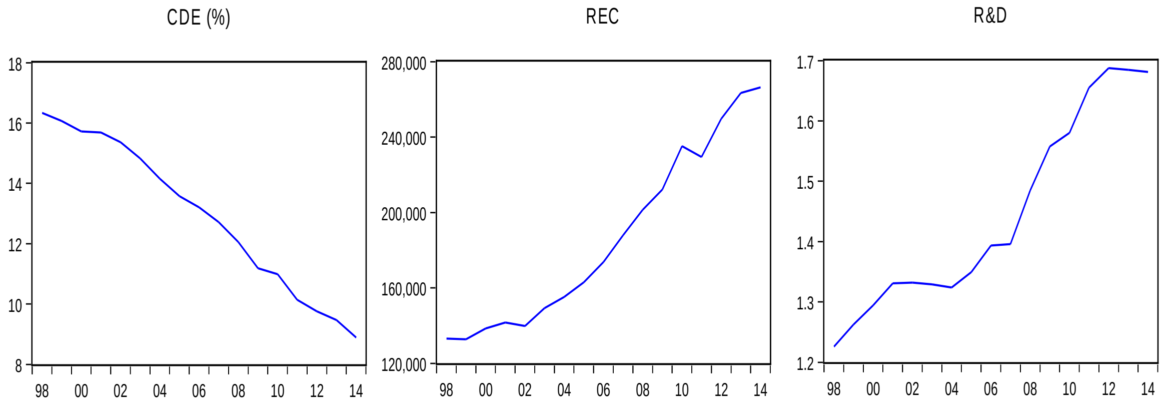
Notes: *** and * indicate significance at the 1% and 10% levels, respectively.

Table 7: Robustness check – long-run renewable energy and emission elasticities

Variable	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.
	Low income economies			High income economies		
REC = f (CDE, PI, R&D, FDI, FM)						
CDE	-1.103***	-15.811	0.000	-1.884***	-46.515	0.000
PI	0.781***	27.246	0.000	2.069***	62.904	0.000
R&D	0.181***	3.406	0.001	0.328***	13.250	0.000
FDI	0.200***	3.527	0.001	-0.051	-1.065	0.288
FM	-0.069*	-1.897	0.060	0.106***	3.282	0.001
CDE = f (POP, PI, R&D, FDI, FM)						
POP	0.337***	19.873	0.000	-0.776***	-94.233	0.000
PI	-0.077***	-3.005	0.003	0.354***	35.449	0.000
R&D	0.085***	3.441	0.001	-0.223***	-12.597	0.000
FDI	-0.102***	-4.296	0.000	0.092***	3.664	0.000
FM	-0.105***	-4.711	0.000	-0.052***	-3.033	0.003
CDE = f (POP, PI, REC, FDI, FM)						
POP	0.599***	32.213	0.000	-0.009	-1.207	0.229
PI	0.135***	4.980	0.000	0.431***	48.886	0.000
REC	-0.063**	-2.195	0.030	-0.243***	-22.725	0.000
FDI	-0.064***	-3.001	0.003	-0.123***	-4.065	0.000
FM	-0.049**	-2.165	0.032	0.020	0.907	0.366

Notes: ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

Figure 1: Key indicators of the sample countries



Notes: CDE is a % of global emissions, while REC and R&D are sample countries averages during the sample period.